A SIMPLE, NEARLY 2D EXPLOSIVELY SHOCKED NdFeB(52) PERMANENT MAGNET AND A COMPARISON TO A CALE CALCULATION SUGGESTING THE MECHANISM FOR MAGNETIC FLUX RELEASE AND SUBSEQUENT EMF PULSE

Jay B. Chase
Care'n Co., Tracy, CA 95377 USA
Stanley Ault
Hyperspectral Sciences, Inc., Cinebar, WA 98533 USA
D. B. Reisman
University of California, Lawrence Livermore National Laboratory, USA

Abstract

Several groups have investigated the phenomenon of the generation of pulsed electrical energy realized from the shocking of modern strong permanent Ferro magnets. The Care'n Co., together with Hyperspectral Sciences, Inc., have performed several experiments, one of which this paper discusses in detail. The shot design and the diagnostics are described in the paper.

The subject magnets (NdFeB(52)) in these investigations were 25 mm long by 25 mm diameter cylindrical solids with the magnetic direction along the cylindrical symmetry axis. Most of the experiments were with the shock front vector aligned along the axis as well. This type of shot has been done and well published by others[1]. The shot described by this paper aligned the shock wave vector perpendicular to the axis and by shaping, entered the magnet in a nearly radial inward fashion. Because the radial velocity of the shock was so much larger than the relief wave from the two ends, the behavior had strong 2D character. This allowed an approximate modeling with the 2D hydro-code CALE in the x-y mode. CALE has a magneto-hydrodynamic modeling capability, but these were not used in the described simulations. The authors were interested in the suggested temperature in the magnetic material behind the shock and how that compared to the magnetic phase diagram. It seems likely that the flux is released due to the material being heated beyond the magnetization boundary but maybe below the Curie temperature. These observations are discussed.

I. EXPERIMENT

The following pictures are of the preparation for this experiment.

Figure 1. Shown is the magnet wrapped with flat cable and insulation.

Figure 2. The magnet is inside the PVC pipe cap.

Figure 3. The magnet is shown.

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14. ABSTRACT

Several groups have investigated the phenomenon of the generation of pulsed electrical energy realized from the shocking of modern strong permanent Ferro magnets. The Caren Co., together with Hyperspectral Sciences, Inc., have performed several experiments, one of which this paper discusses in detail. The shot design and the diagnostics are described in the paper. The subject magnets (NdFeB(52)) in these investigations were 25 mm long by 25 mm diameter cylindrical solids with the magnetic direction along the cylindrical symmetry axis. Most of the experiments were with the shock front vector aligned along the axis as well. This type of shot has been done and well published by others1. The shot described by this paper aligned the shock wave vector perpendicular to the axis and by shaping, entered the magnet in a nearly radial inward fashion. Because the radial velocity of the shock was so much larger than the relief wave from the two ends, the behavior had strong 2D character. This allowed an approximate modeling with the 2D hydro-code CALE in the x-y mode. CALE has a magnetohydrodynamic modeling capability, but these were not used in the described simulations. The authors were interested in the suggested temperature in the magnetic material behind the shock and how that compared to the magnetic phase diagram. It seems likely that the flux is released due to the material being heated beyond the magnetization boundary but maybe below the Curie temperature. These observations are discussed.

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Figure 4. A steel nipple surrounds the explosive.

Figure 5. A view of the explosive loading, showing the Composition C-4 surrounding the magnet.

Figure 6. The Portland cement overcoat container is shown with the steel-PVC shot inside.

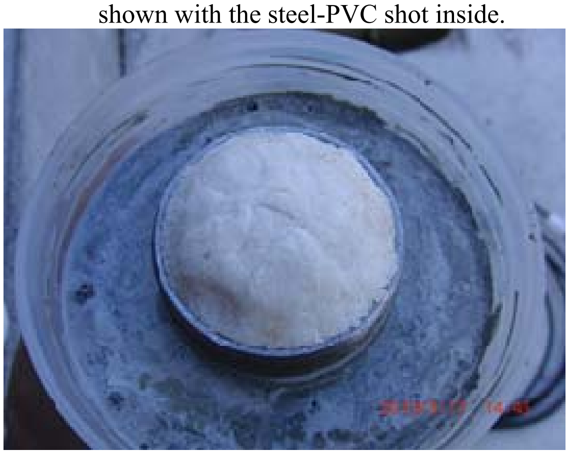

Figure 7. The steel, the C-4, and the cement are shown just before the PVC cap is screwed on.

The explosive was hand packed C-4 and the detonator is a RP-80. The signal was recorded with a high impedance termination so that the record is just the time rate of change of the magnetic flux appearing adjacent to the single turn flat strap wrapped around the magnet.

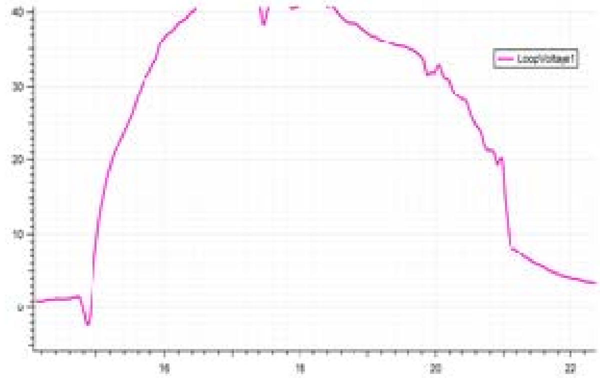

Figure 8. The experimental voltage signal, open circuit, versus microseconds is shown.

II. ANALYSIS

CALE was used as the analysis tool. CALE[2] is an ALE code (written in C) that includes Magneto-Hydrodynamics, but in these simulations the MHD was turned off. Only the effect of the HE generated shock wave heating was being examined. The following series of images are from the CALE simulation.

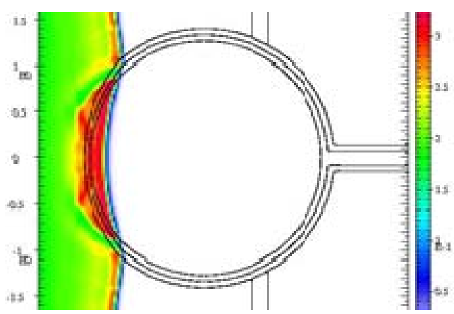

Figure 9. The pressure wave due to the HE (from the left) the units are MegaBars where the maximum shown is 0.36 MB.

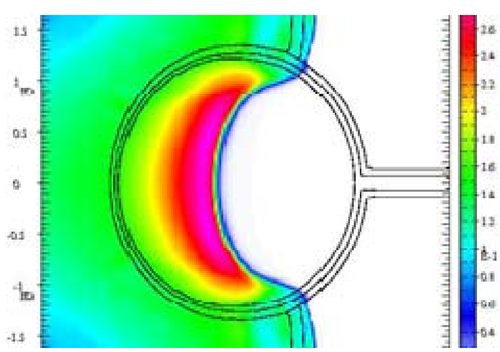

Figure 10. The pressure wave a moment after the HE has been completely expended.

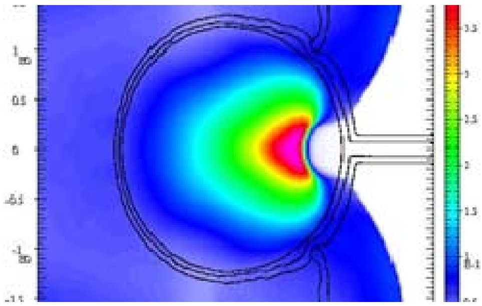

Figure 11. Late time in the propagation of the pressure wave.

CALE will compute and plot the increase in internal specific energy (from ambient) and those plots are shown below. Also included are "line outs" of the specific energy: a trace across the middle of the magnet from left to right.

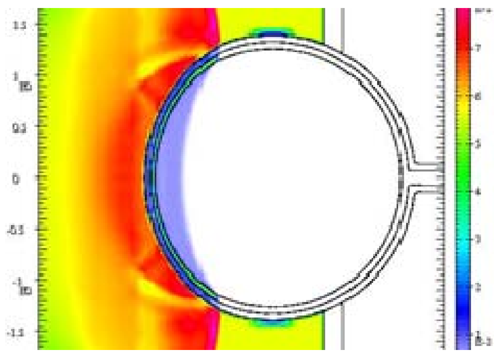

Figure 12. This shows the internal specific energy added because of the shock action of the HE. The units are 10^5 Joules per gram.

Figure 13. A "line out" of the specific energy along the y=0 axis (from left to right of Figure 12) is given. The "x" axis of the plot is the distance in centimeters along CALE's x axis.

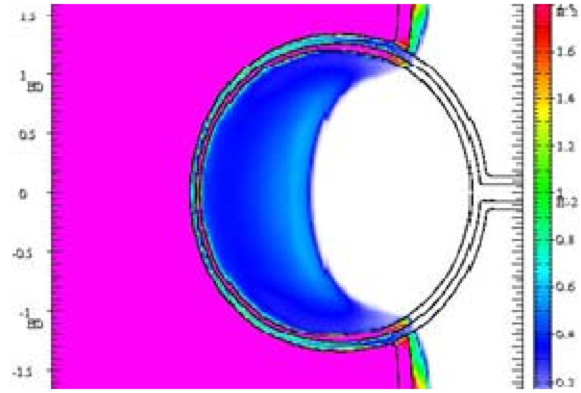

Figure 14. Shown is the internal specific energy midway through the wave crossing of the magnet.

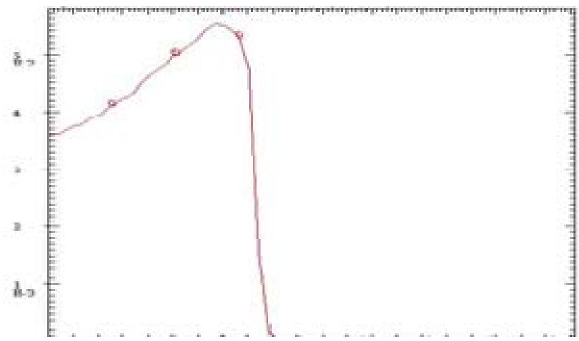

Figure 15. The specific energy "line out" corresponding to Figure 14 is shown.

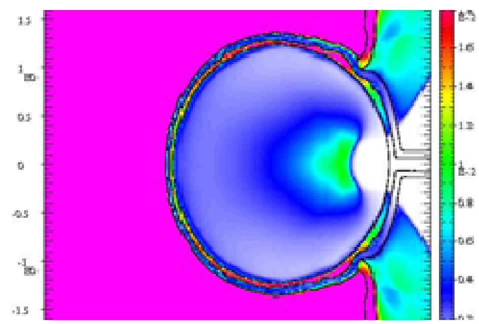

Figure 16. This is the specific energy at a time near the end of the wave crossing.

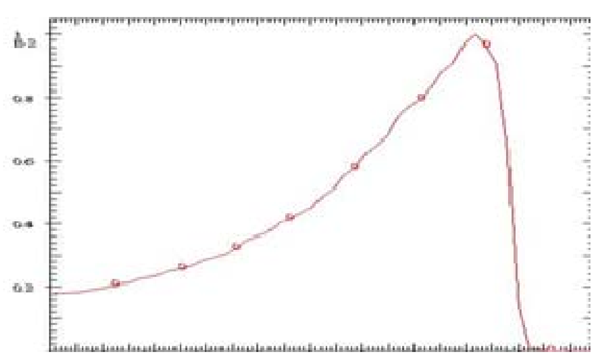

Figure 17. The specific energy "line out" corresponding to Figure 16 is shown.

These specific energy plots can be compared to the magnetic phase diagram for the permanent magnet. A Curie plot for the Ferro-magnet is shown in figure 18. This is a simple theory and is presented here just to indicate the general shape and trend of these phase diagrams. By way of explanation, the x axis is the ratio of the temperature in Kelvin to the Curie temperature for this material and the y axis is the fraction of the residual magnetization for the subject material. As the temperature grows upward, the magnetization residual in the permanent magnet falls until the Curie temperature is attained at which point the magnetic behavior of the material reduces to its paramagnetic state.

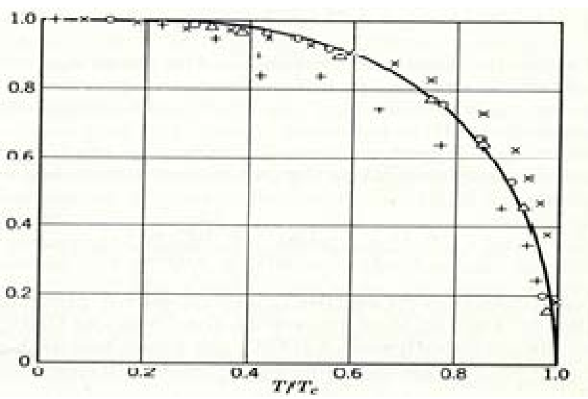

Figure 18. An example of a theoretical ferromagnetic phase diagram where Tc is the Curie temperature in Kelvin and the vertical axis is the fraction of the residual magnetization for the particular material.

The Curie temperature for this particular magnet is 583.15 degrees Kelvin and the residual magnetization is 14.5-14.8 kilogauss. At room temperature and a little above, the specific heat of the magnet material is 0.447 Joules/gK so the Curie temperature is reached at 129.7 Joules/g. That can be converted to the units used by CALE as 0.001297 EU/g and should be compared to the value of the CALE variable "EMAT". A quick look at the plots figures 12-17 indicates that CALE has the material significantly above the Curie temperature, from once shocked throughout the duration of the experiment. So the entire residual magnetization behind the shock must immediately become magnetic induction supported by currents.

If the only current conductor available was the aluminum band wrapped around the magnet in this experiment, then the voltage measured at the terminals of that conductor would be just the time rate of change of the total flux behind the shock front. The flux at any moment is just the product of the magnet's residual magnetization and the area behind the shock front. The rate of change is then just the rate of change of the area multiplied by the residual magnetization.

The area behind the shock wave was determined by tracing the boundary of the shocked region in the CALE simulation and then using the Surveyor's Equation.

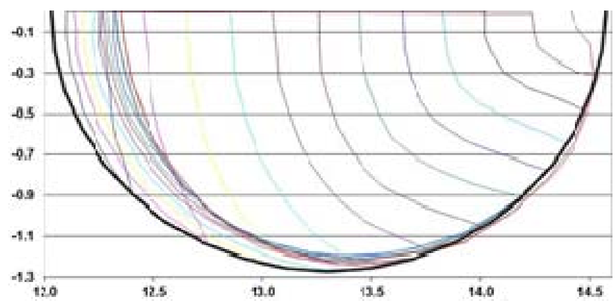

Figure 19. Shown are the boundary lines of the shocked material at a sequence of times during the CALE simulation. These yielded the area as a function of time.

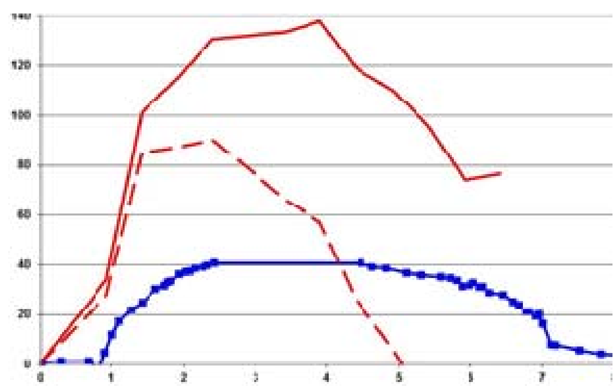

Figure 20. This shows the comparison of the shot data (blue) with a no loss model (solid red) and a simple R/L loss model (dashed red). Volts are on the y axis and microseconds on the x.

III. CONCLUSIONS

The general shape of the no-loss model curve in figure 20 seems satisfying, the time span is a little short, but the magnitude is too high by over a factor of 3. A simple constant resistance flux loss model, appended to the no-loss model, has insufficient loss at the beginning and too much toward the end of the pulse. There are two issues with the models presented both of which may be contributing to the lack of a good match to the data.

1. Rarefactions are certainly racing inward from the two axial ends of the permanent magnet, making the situation three dimensional. The CALE simulations described herein do not include those effects. An experiment in which several of these magnets were lined up to move the ends far away from the data collection loop would correct this limitation.
2. The shocked magnetic material probably retains some conductivity and therefore allows the flow of eddy currents. These effects might be simulated in CALE by using the MHD equations. CALE does not have ferromagnetism, but the residual field intensity could be programmed into the problem. The conductivity dependencies of the shocked material would have to be guessed; it is likely the conductivity reduces with a fall in material density.

IV. REFERENCES

1. S. I. Shkuratov, Et Al, See several papers in the proceedings of the 11th Megagauss Conference, (2006).
2. R. E. Tipton, "The CALE User's Manual. Version 901101", Lawrence Livermore National Laboratory, Livermore, CA. (1990).